

# A comparative reliability analysis of ballistic deployments on binary asteroids

Onur Çelik<sup>a,\*</sup>, Joan Pau Sánchez<sup>b</sup>, Özgür Karatekin<sup>c</sup>, Birgit Ritter<sup>c</sup>

<sup>a</sup>*Department of Space and Astronautical Science, The Graduate University for Advanced Studies (SOKENDAI), 252-5210, Sagamihara, Japan*

<sup>b</sup>*Space Research Group, Centre of Autonomous and Cyber-Physical Systems, Cranfield University, MK43 0AL, Bedford, United Kingdom*

<sup>c</sup>*Reference Systems and Planetology, the Royal Observatory of Belgium (ROB), 1180, Brussels, Belgium*

---

## Abstract

Small body missions can significantly benefit from deploying small landing systems onto the surface of the visited object. Despite the potential benefit that they may bring, deployments of landers in small body environments may entail significant mission design challenges. This paper thus addresses the potential of ballistic landing opportunities in binary asteroid moons from a mission design perspective, particularly focusing on reliability aspects of the trajectories. Two binaries that were previously identified as target bodies in several missions/proposals, Didymos and 1996 FG3, are considered in this paper. The dynamics near them are modelled by means of the Circular Restricted Three Body Problem, which provides a reasonable representation of a standard binary system. Natural landing trajectories that allow both minimum-velocity local-vertical touchdown and deployment from a safe dis-

---

\*Corresponding author

Email addresses: [onur.celik@ac.jaxa.jp](mailto:onur.celik@ac.jaxa.jp) (Onur Çelik),  
[jp.sanchez@cranfield.ac.uk](mailto:jp.sanchez@cranfield.ac.uk) (Joan Pau Sánchez), [ozgur.karatekin@observatory.be](mailto:ozgur.karatekin@observatory.be)  
(Özgür Karatekin), [birgit.ritter@observatory.be](mailto:birgit.ritter@observatory.be) (Birgit Ritter)

*Preprint submitted to Acta Astronautica*

*January 17, 2018*

tance are investigated. Coefficient of restitution values are used as a design parameter to compute the first touchdown speeds that ensure sufficient reliability of landing trajectories. A simple reliability index, which is derived via uncertainty ellipsoid from covariance analysis, is introduced to create a global reliability map across the asteroid surfaces. Assuming  $3\sigma$  deployment errors on the order of 90 m and 2 cm/s, the results show that ballistic landing operations are likely to be successful for larger binary moons if the deployments target near equatorial regions within longitude range  $320^\circ$ – $20^\circ$ . It has also been shown that the deployments to smaller binary moons may require higher accuracy in navigation and deployment systems in their mothership, and/or closer deployment distances.

*Keywords:* Binary asteroids, Landing, Astrodynamics, Trajectory design, Covariance analysis

---

## 1. Introduction

Near-Earth asteroids (NEAs) are the easiest celestial objects to be reached from Earth (excl. the Moon) and offer a unique window to the early stages of accretion and differentiation of the inner planets of the solar system. Among NEAs, asteroids with moons constitute a considerable portion, of about 16% according to recent estimates [1]. However, no mission has aimed for a binary system, since the visit to the Ida-Dactyl system by Galileo spacecraft. On the other hand, among the variety of missions proposed to asteroids, or to small bodies in general, the interest in binary asteroids also seems to grow. The planetary science community has a profound interest in returning to a binary, particularly with rendezvous missions. Such missions have a strong motiva-

tion to settle the debate on the formation of these primitive, information-rich planetary bodies. However, apart from scientific curiosity, and its potential commercial value, missions to binary asteroids are also important as test beds for possible asteroid deflection missions in the future. The threat of asteroid impacts on Earth has been taken seriously and a variety of techniques have been proposed to deflect potentially hazardous asteroids [2]. One of these is the kinetic impactor technique, which involves a high-speed spacecraft which is to intercept a target asteroid in order to change its orbital course to mitigate the risk of a potential impact [3]. Binary asteroids are ideal testbeds to demonstrate the capabilities of kinetic impactors, as change in orbital period of the natural moon of the asteroid, thereafter called the secondary, after an impact would likely be observed by ground-based observation systems. Along with this line of motivations on science and technology demonstration, several Europe- and US-led, or collaborative missions have been proposed within the last decade, such as Marco Polo-R, Binary Asteroid in-situ Exploration (BASiX), and Asteroid Impact and Deflection Assessment (AIDA) [4, 5, 6].

As being the most recent example, the goal of the joint NASA/ESA multi-spacecraft mission proposal AIDA is to test the kinetic impactor technique in the binary asteroid (65803) 1996GT Didymos [6]. Between the proposed two spacecraft, NASA spacecraft Double Asteroid Redirection Test (DART) is planned to perform a high-speed impact on the smaller companion of Didymos (informally called Didymoon). Whereas the ESA spacecraft Asteroid Impact Mission (AIM) has science tasks to provide an observational support to theoretical asteroid deflection studies, which ultimately need the mechanical and structural properties, porosity, cohesion of the target, as well as to

37 collect the necessary data to constrain the formation of this particular binary  
38 system, and possibly provide an evidence for the formation of other binaries,  
39 as well. The original AIM proposal also included MASCOT-2 lander de-  
40 signed by German Aerospace Center (DLR) to perform in-situ observations,  
41 and two CubeSats to be deployed near the binary system [7]. As a response  
42 to the CubeSat call, the Royal Observatory of Belgium (ROB) proposed two  
43 3U CubeSats to land on Didymoon, named as Asteroid Geophysical Explorer  
44 (AGEX) mission [8]. Even if AIM's future appears to be uncertain since 2016  
45 ESA ministerial, the above examples indicate an interest to land small science  
46 packages onto the surface of binary systems.

47     Landing on an asteroid or a comet substantially differs from landing on a  
48 deeper gravity well, such as Mars and the Moon. The extremely weak grav-  
49 itational environment found in small bodies makes purely ballistic descent  
50 trajectories a viable option, since the touchdown velocities can be safely man-  
51 aged only by simple structural modifications on the craft. It could also be  
52 a preferable solution for motherships, such as AIM, to deploy landers from  
53 a safer distance, since the dynamical environment around asteroids imposes  
54 non-negligible risks to low-altitude landing operations. This makes ballistic  
55 landing trajectories ideal conduits for lander craft that possess only minimal  
56 or no control capabilities. However, the very same gravitational environment  
57 entails a completely different challenge: Unless sufficient energy is damped  
58 at touchdown, the lander may well bounce and subsequently escape from  
59 the asteroid, or bounce into a badly illuminated conditions, which would se-  
60 riously jeopardize the mission [9]. Therefore, research on delivering small,  
61 unpowered landers on binary surface has gained a considerable interest.

62 In binary asteroid systems, one can find natural trajectories to deliver sci-  
 63 ence packages by exploiting the three-body problem. Such strategy was first  
 64 studied by Tardivel and Scheeres [10], in which they considered the vicinity  
 65 of equilibrium points of binary systems in Circular Restricted Three-Body  
 66 Problem (CR3BP) as deployment locations, and defined the first intersec-  
 67 tion of a trajectory with the surface as landing [10]. This work was followed  
 68 by a study on the deployment strategy of a small lander in binary asteroid  
 69 1996 FG3, back-up target of Marco Polo-R mission proposal [11]. More-  
 70 over, within the context of MASCOT-2 lander, Tardivel et al. discussed  
 71 passive landing opportunities on Didymoon [12]. Tardivel later published  
 72 an additional study on optimization of ballistic landings in binary asteroid  
 73 [13]. Along the same line of studies, Ferrari and Lavagna performed a tra-  
 74 jectory design study and Monte Carlo simulations against uncertainties for  
 75 MASCOT-2 [14]. In a more recent study, Çelik and Sánchez proposed a  
 76 new technique in CR3BP to search opportunities for ballistic soft landing in  
 77 binary asteroids [15]. This technique defines a landing in local vertical and  
 78 utilizes a bisection search algorithm to find minimum energy trajectories in  
 79 backwards propagation from the surface.

80 This paper focuses on design aspects of ballistic landings of small lan-  
 81 ders onto the surfaces natural moons of binary asteroids. Çelik and Sánchez  
 82 (2017) previously showed that landing trajectories onto larger companions of  
 83 binaries (thereafter called as the primaries) entail higher energy landing tra-  
 84 jectories, which; on the one hand may put the payload on the lander at risk  
 85 due to the higher touchdown velocities, and on the other hand, do not guar-  
 86 antee that the lander will remain in the surface of the primary, unless very

low coefficient of restitution can be ensured [15]. Hence, this paper focuses only on landing in the secondary, which was previously shown to potentially enable ballistic soft landing [15]. The paper particularly addresses the reliability aspects of the deployment operations under realistic uncertainties and errors in navigation and deployment systems. Two binaries are selected as targets: Didymos and 1996 FG3. A spherical shape and point mass gravity are assumed for both companions. A dense grid of first touchdown points is created and distributed homogeneously on the surface, whose locations are described by their latitudes and longitudes. Trajectories are then generated from each point in by applying the methodology developed in [15]. This allows us to obtain nominal trajectories under ideal conditions, as well as to generate a database of reachable regions and characteristics of landings on the surface as a function of landing location. One of the useful information in the database is touchdown speeds, which is the only parameter that characterizes the landing trajectory for a given landing site, due to the definition of the local vertical landing. Thus, they can be used to compute the worst case estimation of the required energy damping, or coefficient of restitution, in order to stay near the binary system after the first touchdown. In this paper, first, the reliability of landing trajectories to reachable locations with the worst case coefficient of restitution are investigated in a simple deployment model with the covariance analysis. The covariance matrices for a global set of landing conditions are propagated to the surface from the deployment points, and the regions with more robust landing conditions are identified.

The reliability of the nominal trajectories are next discussed by generating landing conditions for a specific coefficient of restitution, navigation and

112 deployment errors. A reliability index is introduced from the cross-sectional  
 113 area of uncertainty ellipsoid (computed after the covariance propagation)  
 114 in the local topocentric frame of landing site and the cross-sectional area of  
 115 subject asteroid, in order to assess the robustness of the deployment operation  
 116 at different landing sites. The covariance analysis and the reliability index are  
 117 tested by Monte Carlo analyses for further assessment of the methodology.  
 118 By creating a multifaceted global reliability map of landings, this paper aims  
 119 to draw a preliminary conclusion about how non-idealities might possibly  
 120 affect the success of landing operations of an unpowered lander in binary  
 121 asteroid surfaces.

122 The remainder of the paper is structured as follows: Section 2 intro-  
 123 duces the binary asteroid model; Section 3 introduces the trajectory design  
 124 methodology and the deployment model, and discusses the results of land-  
 125 ing speeds, coefficients of restitution and deployment opportunities for the  
 126 minimum touchdown speed case. Section 4 describes the navigation model  
 127 and discusses the results of uncertainty analysis. Finally, Section 5 provides  
 128 conclusions and final remarks.

## 129 **2. Binary Asteroid Model**

130 This paper considers (65803) 1996GT Didymos and (175706) 1996 FG3  
 131 as targets for our ballistic landing analysis. These are previously identified  
 132 targets (with rather frequent launch opportunities) of at least three mission  
 133 proposals, with a small lander option [4, 5, 6]. Moreover, their physical  
 134 properties are quite different from each other, as shown in Table 1 below.

135 As mentioned earlier, this paper assumes binary asteroids which are com-

Table 1: Physical properties of (65803) Didymos & 1996FG3. Didymain and 1996 FG<sub>3</sub> A denote the primaries, whereas Didymoon and 1996 FG<sub>3</sub>-B denote the secondaries in the binary systems, respectively.

Property	Didymain	Didymoon	1996 FG3-A	1996 FG3-B
Diameter [km]	0.775	0.163	1.690	0.490
Density [kg/m <sup>3</sup> ]	2146		1300	
Mass [kg]	5.23 x 10 <sup>11</sup>	4.89 x 10 <sup>9</sup>	3.29 x 10 <sup>12</sup>	8.01 x 10 <sup>10</sup>
Mass parameter ( $\frac{m_2}{m_1+m_2}$ ) [-]	0.0092		0.0238	
Mutual orbit radius [km]	1.18		3.00	
Mutual orbit period [h]	11.9		16.15	

posed of two spherical bodies with the same constant density. The binary nature of the asteroids allows us to use the CR3BP as the dynamical framework to the motion of a lander, whose details are going to be discussed in the next section. The CR3BP is generally derived in the normalized distance, time and mass units, of which the normalized mass (mass parameter) is provided for both asteroids in Table 1. Mass parameter is one of two main parameters that uniquely defines the dynamical environment near the binary asteroid, together with the ratio between the mutual orbit semi-major axis and the primary diameter (the  $a$ -to- $D_{pri}$  ratio). The spherical asteroid and the same density assumptions conveniently allow us to redefine mass parameter in terms of the secondary-to-primary diameter ratio (the  $D_{sec}$ -to- $D_{pri}$  ratio). Please, refer to [15] for more comprehensive description and justification of the method. In Çelik and Sánchez [15], the statistics of these two properties among the NEA binaries with known (not assumed) densities were investigated, and it was found that the  $D_{sec}$ -to- $D_{pri}$  ratio has a mean of 0.28,



151 while the  $a\text{-to-}D_{pri}$  ratio has a mean of 2.20 [15]. Those two ratio properties  
 152 are 0.21 and 1.52 for Didymos, and 0.29 and 1.78 for 1996FG3, respectively,  
 153 and this locates them near the *average* ratio properties of the NEA binaries.  
 154 This suggests that the analyses that will be presented in the next sections not  
 155 only cover a wider range of binaries in size, but also a good representation of  
 156 the currently known binary population in terms of the ratio properties. This  
 157 result has also been illustrated in Figure 1, which presents the distribution  
 158 of the ratio properties of the NEA binaries with known densities. It can be  
 159 noted from the figure that Didymos and 1996FG3 fall near the middle of the  
 160 data points.

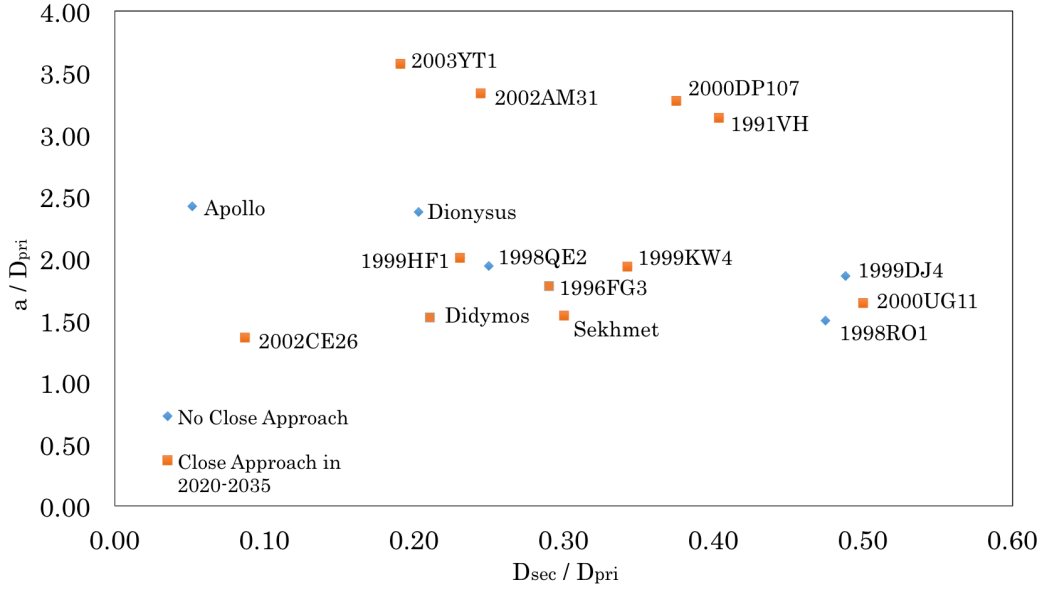


Figure 1: Close approaches of the NEA binaries ( $<0.2$  AU) in 2020-2035 time frame. ( $a$ : semi-major axis of secondary orbit around primary;  $D_{pri}$  is diameter of a spherical primary and  $D_{sec}$  is diameter of a spherical secondary.

161 NEA binaries with known densities are represented by a square point in

162 the figure if the referred binary is due to undergo a close encounter with  
 163 the Earth during an hypothetical launch window between 2020-2035. Here,  
 164 close approach refers to a minimum distance with the Earth of less than 0.2  
 165 AU, within which a mission would be justifiable with low energy trajectories  
 166 [16]. Among the whole set of NEA binaries, 2000 DP107, 1991 VH and 2000  
 167 UG11 are also interesting objects, since a patched conic trajectory analysis  
 168 identifies these objects also as accessible during their close approach<sup>1</sup>. These  
 169 binaries would also be of interest, since as shown in Fig. 1, their semi-major  
 170 axis and size ratios are far from the observed average values. Nevertheless,  
 171 for the sake of simplicity, only two binary asteroids Didymos and 1996FG3  
 172 are going to be analyzed in next sections.

### 173 **3. Landing Trajectory Design**

174 Let us consider a mothership, in its operational orbit, at a safe distance  
 175 from the binary system's barycentre. A passive lander (or a "science pack-  
 176 age") can be sent onto the surface of one or both of binary companions from  
 177 this mothership by exploiting the natural dynamics around the binary sys-  
 178 tem. As mentioned earlier, landing trajectories in this dynamical scheme  
 179 can be designed in the framework of Circular Restricted Three-Body Prob-  
 180 lem (CR3BP), in which third body (i.e. lander) is assumed to move under the  
 181 gravitational attraction of primary and secondary (i.e. binary companions)  
 182 without effecting their motion about their common centre of mass. The dy-  
 183 namical model is traditionally derived in the rotational frame, whose center

---

<sup>1</sup>Patched conic accessibility analysis considered Earth departure  $v_\infty$  less than 6 km/s  
 and launch performances as expected for Ariane 6.2.

184 is at the barycenter of larger bodies, with x-axis on the line connecting the  
185 primary and the secondary, z-axis defined in the direction of the mutual orbit  
186 normal and y-axis completing triad [17]. Hence, unless otherwise stated, the  
187 models and the results will be provided in this rotating barycentric reference  
188 frame.

189 The CR3BP exhibits five equilibria, called the Lagrange points (L1-L5),  
190 and five different regimes of motion, expressed in zero-velocity surfaces (ZVS)  
191 [17]. For our notional mothership, an operational orbit can be defined in the  
192 exterior realm of ZVS, in which the L2 point is closed so that no natural  
193 motion is allowed to the interior realm. In this setting, the L2 point presents  
194 the lowest energy gate to reach the interior region. Thus, a simple spring  
195 mechanism available on a mothership can provide a gentle push to increase  
196 the lander’s energy in order to open up ZVS at the L2 point and allow motion  
197 to the interior realm. The operational orbit of a mothership and deployment  
198 strategy are illustrated in Fig. 2.

199 The landing trajectory design in such scenario is tackled in the ground-  
200 work study performed by Çelik and Sánchez in the context of a hypothetical  
201 binary asteroid, whose properties are a good representation of the known  
202 NEA population [15]. In this study, landing is defined in the local vertical of  
203 a landing site and described by its latitude and longitude. Such description  
204 has the clear advantage of defining a landing by only one parameter, i.e.  
205 touchdown speed ( $v_{T/D}$ ), once a specific landing location is defined. The ini-  
206 tial state vectors are then propagated backwards from the landing locations  
207 on the surface to the exterior realm of ZVS in a specially developed bisection  
208 algorithm [15]. The algorithm searches for the minimum energy landings in

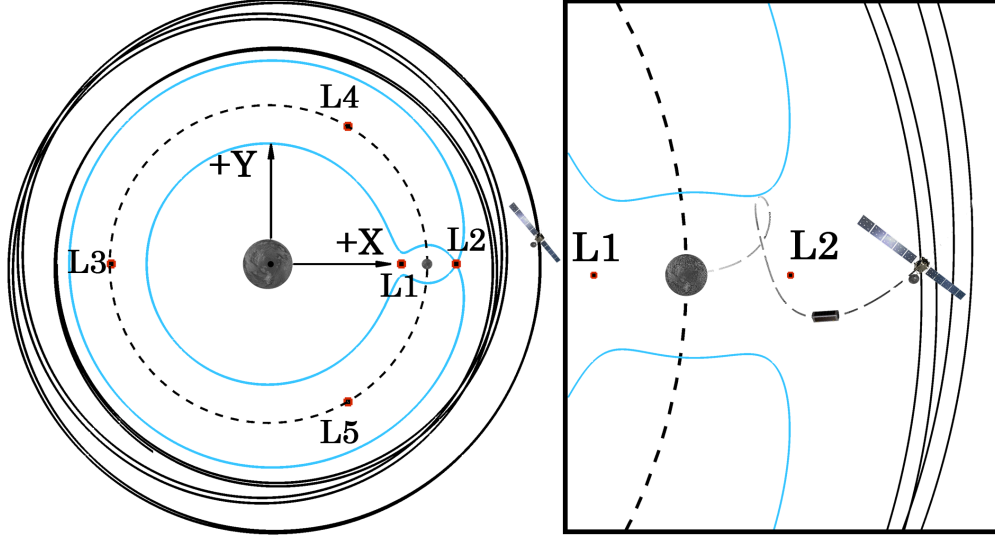


Figure 2: Mission architecture. Operational scenario of the mothership, ZVS closed at L2 (Left). The deployment provides the energy to open ZVS up at L2 (Right).

209 a reverse-engineered, iterative manner from the surface to exterior region of  
 210 ZVS. It then allows trajectories to be designed for any arbitrary latitude–  
 211 longitude pairs on the surface for any sizes of binary asteroids. Hence, it  
 212 generates an overall picture for various features of landing, e.g. energies,  
 213 speeds and required maximum coefficient of restitution ( $\epsilon$ ) values. Moreover,  
 214 after the resulting trajectories are propagated sufficiently long time, any part  
 215 of the trajectory that lies beyond the ZVS with the L2 point energy can be  
 216 seen as a potential deployment location. The minimum deployment velocities  
 217 at those locations can be estimated by computing the necessary velocity that  
 218 closes ZVS at the L2 point, which therefore corresponds to open up ZVS at  
 219 the L2 point in forward propagation mode, to allow motion to the interior  
 220 realm. For much more detailed explanation on the methodology, the reader

221 is encouraged to refer to the work of Çelik and Sánchez [15].

### 222 3.1. Landing speed and energy damping

223 The results of landing speeds are provided in Fig. 3. The secondary is  
224 assumed to be tidally locked, hence the attitude of secondary can be assumed  
225 fixed in the synodic reference frame.  $0^\circ$  represents the prime meridian whose  
226 point is arbitrarily defined as to be on the x-axis, directly facing the L2 point.

227 Figure 3 shows that both binaries show similar characteristics in terms  
228 of minimum touchdown speeds. Minimum touchdown speeds are observed  
229 at the landing sites near the L2 point and in the trailing edge of the far  
230 side. Approximately half of the secondary surface is available under 10 cm/s  
231 for Didymoon ( $\sim 47\%$ ) and 20 cm/s for 1996 FG3 ( $\sim 44\%$ ). The minimum  
232 computed touchdown speeds in Didymoon and 1996 FG3-B are 5.8 cm/s and  
233 14.9 cm/s respectively, at the closest point to the L2 point. It is noteworthy  
234 that these values are below the two-body escape speed of both Didymos (32.4  
235 cm/s) and 1996 FG3 (57.6 cm/s). These escape speeds were computed at  
236 the landing point closest to the L2 point as the sum of escape speeds of both  
237 bodies. However, as shown by the results in Figure 3, the classical escape  
238 velocity is a misleading result, since in order to open up the ZVS at the L2  
239 point, one requires energies that can be achieved with speeds smaller than  
240 5 cm/s. Therefore, a lander can in fact escape with speeds lower than the  
241 two-body escape velocity if a proper geometry of the escape motion is found.

242 As discussed earlier, the trajectory design methodology also enables us  
243 to estimate the minimum coefficient of restitution  $\epsilon$  on the surface.  $\epsilon$  in  
244 this study refers to the simple interaction between surface and the landing  
245 spacecraft with a specific value, similar to a bouncing ball on a surface and

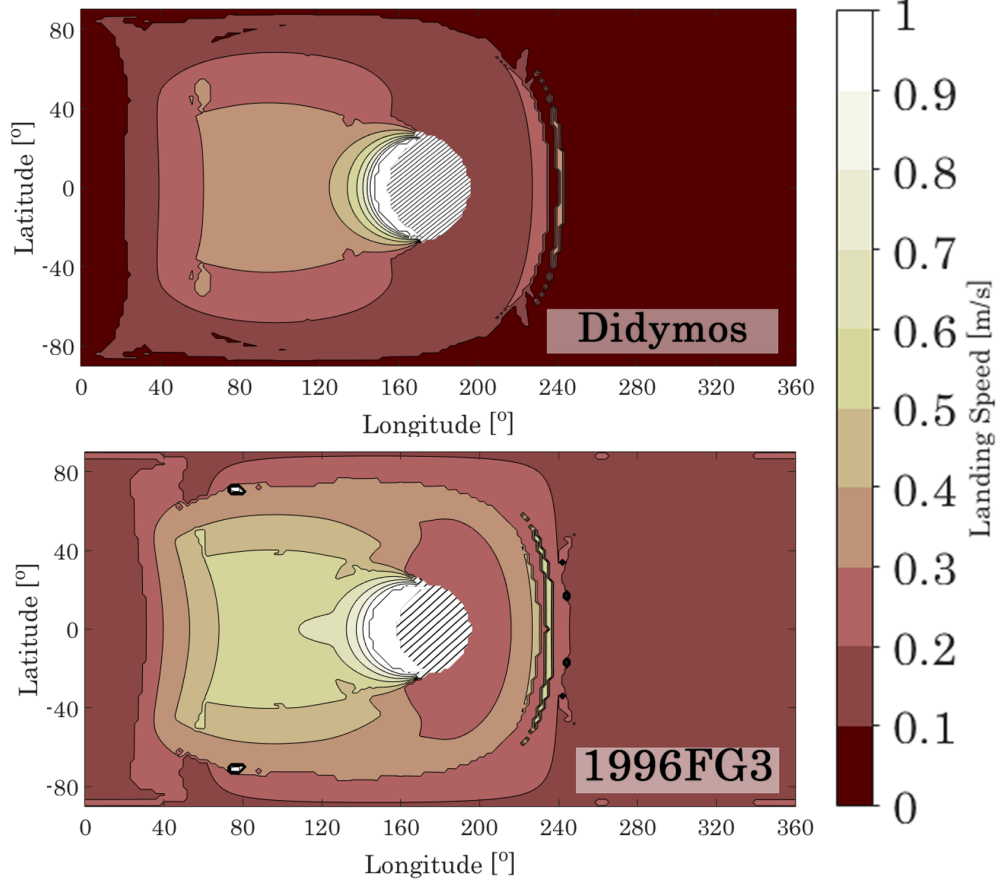


Figure 3: Minimum touchdown speeds on Didymos and 1996FG3-B surface. The diagonal texture in the middle of figures shows unavailability of ballistic landing to those regions with the trajectory design algorithm discussed in the text. The estimated two-body escape speeds are 32.4 cm/s and 57.6 cm/s for Didymos and 1996FG3, respectively.

246 can be described in both local vertical and local horizontal. However, this  
 247 paper only concerns with  $\epsilon$  values in local vertical, and assumes that the  
 248 outgoing velocity is in the same plane as the incoming velocity and the surface  
 249 normal vector. This may change due to surface features, such as boulders or

250 rocks, however that is not considered here.  $\epsilon$  value then defines the energy  
 251 dissipation due to surface properties, as in Eq. 1 in its simplest way.

$$\begin{aligned}
 \mathbf{v}_{LV}^- &= (\hat{\mathbf{n}} \cdot \mathbf{v}) \cdot \mathbf{v} \\
 \mathbf{v}_{LV}^+ &= -\epsilon (\hat{\mathbf{n}} \cdot \mathbf{v}) \cdot \mathbf{v} \\
 \implies \mathbf{v}_{LV}^+ &= -\epsilon \mathbf{v}_{LV}^-
 \end{aligned} \tag{1}$$

252 where  $\mathbf{v}_{LV}$  is the local vertical velocity,  $\hat{\mathbf{n}}$  is local normal unit vector and su-  
 253 perscripts  $(-)$  and  $(+)$  denote incoming and outgoing velocities, respectively.  
 254  $\epsilon$  values must typically be between 0 and 1, but it may be considerably  
 255 different in local horizontal and vertical directions [18, 19].

256 We can now compute  $\epsilon$  values to close ZVS at the L1 point for landings  
 257 depicted in Fig 3. Basically, this is a rough estimate of how much energy  
 258 needs to be dissipated at touchdown, so that motion of a lander would be  
 259 trapped near the secondary of binary system. In the rest of the paper,  $\epsilon$  will  
 260 always refer to the required coefficient of restitution to reduce the energy  
 261 below that of the L1 point. The results are presented in Fig. 4.

262 In a clear agreement with the results in Fig. 3, the regions of lowest touch-  
 263 down speeds show higher  $\epsilon$  values, hinting that very little energy dissipation  
 264 would be enough to keep a lander near the binary systems. In the regions of  
 265 higher touchdown speeds, on the other hand, the  $\epsilon$  values begin to decrease  
 266 to levels, for which a lander would likely require an active landing system.  
 267 Thus, for a purely passive landing, the regions with low landing speed and  
 268 high  $\epsilon$  appear to be more attractive options to consider for deployment.

269 Figure 4 reveals important insights at first glance into the feasibility of the

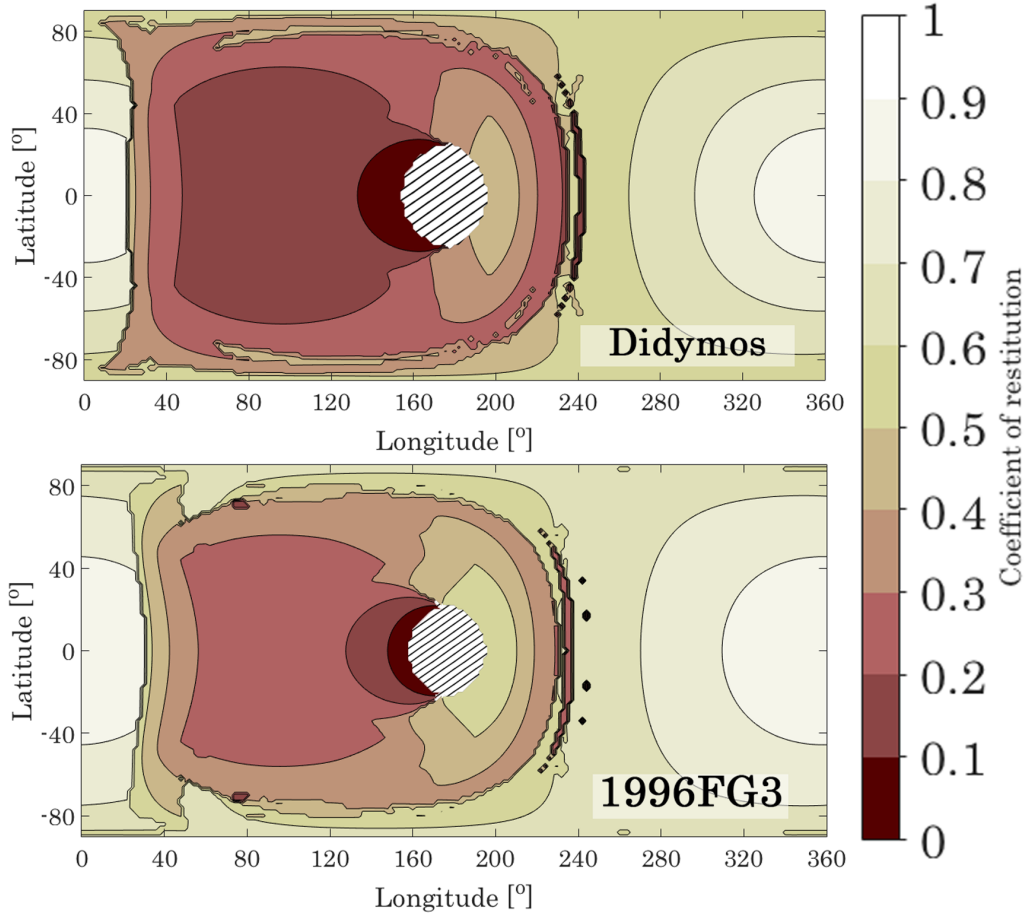


Figure 4: Required coefficient of restitution ( $\epsilon$ ) to close ZVS at the L1 point for both secondaries.

ballistic landing in binary asteroid systems. It should be noted at this point that the coefficient of restitution value in the sampling horn of Hayabusa at the touchdown was measured as  $\sim 0.85$  [20]. While this value has large uncertainties, Philae’s touchdown on comet 67P/Churyumov-Gerasimenko revealed that the comet surface is “strongly damping” with  $\epsilon$  values varying between  $\sim 0.2$ - $0.5$  [21]. Taking this information into account, it is clear that



276 assuming a conservative estimate of  $\sim 0.9$  for  $\epsilon$  would allow only some reduced  
 277 regions in the far side of the secondary. However, more recent theoretical and  
 278 experimental studies suggest that appropriate structural design solutions may  
 279 well allow  $\epsilon \sim 0.6$ , or even lower, in the asteroid surfaces [22, 23].

280 The maximum expected  $\epsilon$  value on the current mission scenarios is there-  
 281 fore  $\sim 0.6$ . The results on Fig.4 allow enough room to be more conservative to  
 282 provide a margin to this value, therefore  $\epsilon = 0.7$  was chosen as the minimum  
 283 feasibility criteria of landing operations. Regions that exhibit lower than  
 284 this  $\epsilon$  value are going to be discarded as infeasible. Nevertheless, as shown  
 285 in Çelik and Sánchez [15], the results in Fig. 4 are likely to be the worst case  
 286 estimates of the actual  $\epsilon$  values, since the motion after a bounce may allow  
 287 further contact with the surface, i.e. more opportunities for energy damping,  
 288 before the lander rests on the surface. For more information, the reader may  
 289 refer to the other available works in the literature [18, 24, 25, 19, 21].

### 290 3.2. Deployment model

291 In the deployment operation, the mothership is likely to release the lander  
 292 while on a trajectory taking it near to a binary, but still safe according to  
 293 the ZVS discussion in Section 3. Thus, we assume that a release trajectory  
 294 has a periapsis at the deployment point, and an apoapsis near the sphere  
 295 of influence (SOI) of binary system. Then, at the deployment point the  
 296 mothership shall have a normalized velocity  $\mathbf{v}_{S/C}$ , computed through elliptic  
 297 Keplerian orbits as:

$$\mathbf{v}_{S/C} = \left( \sqrt{\frac{2}{r_{release}} - \frac{2}{r_{release} + r_{SOI}}} - r_{release} \right) \hat{\boldsymbol{\theta}} \quad (2)$$

298 where  $\hat{\boldsymbol{\theta}} = \hat{\mathbf{h}} \times \hat{\mathbf{r}}$ ,  $\hat{\mathbf{r}}$  is the release position unit radius vector and  $\hat{\mathbf{h}}$  is the  
 299 direction of the ballistic descent trajectory momentum vector. The initial  
 300 state vector of the ballistic descent  $[\mathbf{r}_{release} \ \mathbf{v}_{release}]$  was computed with the  
 301 aforementioned bisection algorithm [15]. The state vector  $[\mathbf{r}_{release} \ \mathbf{v}_{release}]$  is  
 302 chosen such that two constraints are satisfied:

- 303 • Duration of the descent trajectory must be less than 12 h.
- 304 • Mothership distance to the barycenter of the binary must be greater  
 305 than 1.25 times the distance of the L2 point to the barycentre,  $r_{L2}$ .

306 The duration of the descent is set to ensure relatively shorter operation  
 307 times, while also allowing plenty of opportunities for deployment. And the  
 308 minimum deployment altitude is scaled with the L2 point distance so that  
 309 the mothership will always be in a safe distance from the secondary. This  
 310 distance can be increased or decreased during the design phase in a trade-off  
 311 between the risk on the mothership and the robustness of the deployment  
 312 operations. However, note that the deployment distance must always be  
 313 greater than or equal to the L2 point distance to barycentre due to the  
 314 particular characteristic of the ballistic landing discussed here. Here, it was  
 315 chosen arbitrarily with the purpose to define a safer deployment scenario  
 316 than those studied in previous work by the authors [26], since the further  
 317 from the secondary surface the more dynamically stable. The deployment  
 318 altitude in this case corresponds to  $\sim 440$  m for Didymos,  $\sim 1285$  m for 1996  
 319 FG3 from the secondary surface when measured on the x-axis of the rotating  
 320 reference frame.

321 The above deployment model and the constraints are an attempt to gen-  
 322 eralize the deployment model for any binary system of interest. Depending  
 323 on the dynamical characteristics of a target, multitudes of orbits can be ex-  
 324 ploited to fulfill operational and scientific requirements. Examples of those  
 325 include direct and retrograde interior orbits around primaries, quasi-satellite  
 326 orbits around the secondary, and direct and retrograde exterior and termi-  
 327 nator orbits around the binary system, or even orbits around equilateral  
 328 Lagrange points of the binary systems [27, 28]. Some of the example orbits  
 329 may enable better deployment conditions for certain regions (e.g. poles), but  
 330 this is out of scope of the paper.

331 The deployment spring mechanism in the mothership must then provide  
 332 an impulse to the lander such that:

$$\mathbf{v}_{spring} = \mathbf{v}_{release} - \mathbf{v}_{S/C} \quad (3)$$

333 Note that, ignoring navigation errors, the release location  $\mathbf{r}_{release}$  is as-  
 334 sumed to coincide with the position of the mothership,  $\mathbf{r}_{S/C}$ , at the release  
 335 time. According to the above deployment model, a relatively reduced region  
 336 of the secondary is available for landing at coefficient of restitution  $\epsilon > 0.7$ ,  
 337 and those regions are depicted in Fig. 5. Some regions in the far side are no  
 338 longer reachable, due to the fact that the ballistic descent trajectory takes  
 339 more than 12 hours from the given deployment distance. This however could  
 340 be solved by allowing touchdown speeds larger than the minimum touchdown  
 341 velocity (in Fig. 3), as will be seen in the next section.

342 Most of the available deployments are possible with deployment speeds on  
 343 the order of  $\sim 5$  cm/s or below, and no deployments are observed with speeds

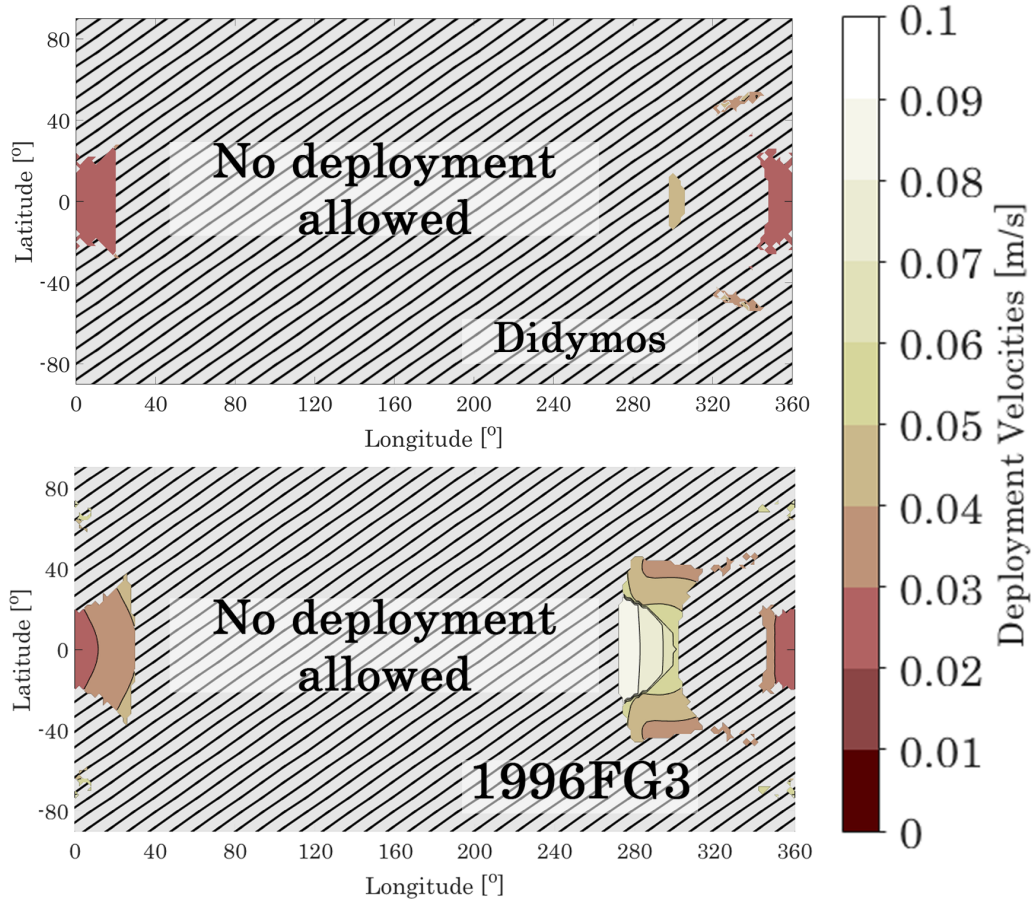


Figure 5: Deployment opportunities with minimum possible touchdown speeds

344 higher than 10 cm/s. While the most deployments to the Didymoon surface  
 345 are possible with  $\sim 2$  cm/s, the deployments to the 1996 FG3-B surface are  
 346 possible  $\sim 3$  cm/s and above. Note that the Philae's separation speed from  
 347 Rosetta was designed to be between 5–50 cm/s with a redundant system  
 348 capable of 18 cm/s [19]. AIM's deployment mechanism, on the other hand,  
 349 is designed to provide 2–5 cm/s within  $\pm 1$  cm/s accuracy [29]. Thus, it seems  
 350 that a separation mechanism whose performance in between that of AIM and

351 Rosetta can easily fulfill the deployment demands of both targets.

#### 352 **4. Reliability of ballistic landing trajectories**

353 Ballistic landing trajectories show a compelling prospect to be utilized as  
354 a landing strategy, however they also come with their inherent instabilities  
355 [30]. Furthermore, trajectories that are generated by the strategy described  
356 above are largely idealized with relatively ad-hoc constraints, and it is thus  
357 necessary to assess their robustness also against the non-ideal conditions.  
358 Particularly, deployments will be affected by the orbit determination errors of  
359 the mothership, as well as by the inaccuracies in the deployment mechanism.

360 Many other error sources and perturbations also exist, such as attitude  
361 errors or perturbations due to the highly irregular nature of asteroids, par-  
362 ticularly in terms of gravity field and shape. This study, however, is only  
363 concerned with the GNC and the deployment aspects of non-idealities. The  
364 authors' previous works also considered the density (hence gravity) errors in  
365 the secondaries [26, 31], however Didymoon and 1996 FG3-B constitute only  
366  $\sim 1.2\%$  and  $\sim 2.5\%$  of the total mass of their respective systems according to  
367 the information in Table 1. It was shown to have a limited effect in the overall  
368 robustness of trajectories to reach the surface as compared to the GNC and  
369 deployment errors [31, 26], therefore these were not considered in the current  
370 study. However, errors in the gravity field of the secondaries may be critical  
371 especially in long duration ballistic landing trajectories, and a special care  
372 should be taken [32]. Furthermore, solar radiation pressure is found to have  
373 a negligible impact due to short time scale of landings. As a final remark,  
374 the fact that the spherical shape is assumed may not necessarily be consid-

375 ered as a source of error, because if the shape of the binary was known, the  
 376 same strategy could be used to compute new trajectories, as was done for  
 377 Philae’s descent trajectory computation [33]. Table 2 summarizes the error  
 378 and uncertainty values considered in the paper.

Table 2: Uncertainty and error sources.

Source	$3\sigma$
GNC position accuracy	$\pm 90$ m
GNC velocity accuracy	$\pm 2$ cm/s
Spring magnitude error	3%
Spring angle error	$\pm 4^\circ$

379 The values in the table are realistic and found during the design process  
 380 of AIM. It should be noted that the GNC position error in Table 2 is three  
 381 times or more than those considered in the previous studies by the authors  
 382 [31, 26, 34]. This is due to the GNC system design of AIM, which assumes  
 383 no altimeter, but pure relative navigation, with a fusion of image tracking  
 384 and the other sensors onboard [35]. The GNC system therefore requires a  
 385 comparison of two (or more) consecutive images and measurement of indirect  
 386 sources (star tracker and inertial measurement units (IMUs)) to measure the  
 387 range to the body, hence inherently increasing the error magnitude.

#### 388 4.1. Deployment covariance analysis

389 A convenient way to analyze impact of the uncertainty and error sources  
 390 is covariance analysis. The covariance matrix in this context provides a linear  
 391 approximation of the sensitivity of a nominal landing trajectory against the

392 non-idealities. We can translate the information in Table 2 into a diagonal  
 393 covariance matrix at release time ( $t_R$ )  $Q_R$  as:

$$Q_R = \left[ \begin{array}{ccc|ccc} \sigma_x^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma_y^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma_y^2 & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & \sigma_{v_x}^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma_{v_y}^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma_{v_z}^2 \end{array} \right] \quad (4)$$

394 where the diagonal values contain variance of errors in each component of  
 395 the state vector. At the instant of deployment, lander and mothership are  
 396 assumed to be at the same position, hence the GNC errors applies to the the  
 397 lander initial state.

398 The spring angle and magnitude errors, as well as the GNC errors in ve-  
 399 locity, will affect the velocity components of the Cartesian covariance matrix  
 400 in Eq. 4. For the spring errors, a Monte Carlo sampling with 10000 random  
 401 values was used to estimate the variance of the velocity components due to  
 402 the spring errors. These variances are then sum to those of the GNC.

403  $Q_R$  can then be propagated to the asteroid surface via state transition  
 404 matrix  $\Phi$  of the nominal trajectory. At the time of touchdown,  $t_{T/D}$ , the  
 405 covariance matrix can be computed as below:

$$Q_{T/D}(t_{T/D}) = \Phi(t_{T/D}, t_R) Q_R(t_R) \Phi^{-1}(t_{T/D}, t_R) \quad (5)$$

406 where subscripts  $T/D$  and  $R$  denote touchdown and release respectively. The  
 407 position errors at touchdown are represented by the  $3 \times 3$  submatrix in the  
 408 top left corner of the covariance matrix at touchdown time  $Q(t_{T/D})$ :

$$Q_{T/D} = \left[ \begin{array}{ccc|c} Q_{xx}^{T/D} & Q_{xy}^{T/D} & Q_{xz}^{T/D} & \\ Q_{yx}^{T/D} & Q_{yy}^{T/D} & Q_{yz}^{T/D} & Q_{TR} \\ Q_{zx}^{T/D} & Q_{zy}^{T/D} & Q_{zz}^{T/D} & \\ \hline & Q_{BL} & & Q_{BR} \end{array} \right] \quad (6)$$

409 However, the position would best be represented in the topocentric co-  
 410 ordinate frame using the principal axes of the secondary of the binary of  
 411 interest. Therefore, the resulting matrix  $Q_{T/D}$  after propagation is rotated  
 412 to the local topocentric frame of the landing site [36]. The  $3 \times 3$  top left sub-  
 413 matrix in Eq. 6 is decomposed into its eigenvalues and eigenvectors. In such  
 414 approach, the submatrix in Eq. 6 can be represented in the following form:

$$Q_P(t_{T/D}) = \begin{bmatrix} a^2 & 0 & 0 \\ 0 & b^2 & 0 \\ 0 & 0 & c^2 \end{bmatrix} \quad (7)$$

415 where the subscript  $P$  denotes position. Square root of the diagonal non-zero  
 416 elements  $a^2$  and  $b^2$  in Eq. 7 are semi-major and semi-minor axes ( $a$ ,  $b$ ) of the  
 417 footprint of the uncertainty ellipsoid representing the  $1\sigma$  Gausssian distribu-  
 418 tion of the deployment errors as projected onto the landing site. Given the  
 419 assumed Gaussian distributions for uncertainties and errors, the probability  
 420 to obtain a landing trajectory touching-down outside the 1-sigma distribu-  
 421 tion footprint is high (i.e.  $\sim 61\%$  in a 2D distribution). The probability to  
 422 fall instead outside the 2-sigma footprint ( $2a$ ,  $2b$ ) is of about of 14%, while  
 423 outside the 3-sigma footprint ( $3a$ ,  $3b$ ) would only be of about 1% [36]. Since



424 a small lander may well be used in a much more daring operation than a  
 425 traditional spacecraft, we will assume for now that a landing opportunity  
 426 with a  $2\sigma$  footprint smaller than the cross-sectional area of the secondary  
 427 would be a landing opportunity with an acceptable risk.

Thus, a reliability index can be defined such as:

$$A_{2\sigma} = \frac{\pi(2a \cdot 2b)}{\pi \cdot r_s^2} = \frac{4ab}{r_s^2} \quad (8)$$

428 where  $A_{2\sigma}$  represents the area of the 2-sigma distribution footprint in units  
 429 of the cross-sectional area of the secondary and  $r_s$  is the radius of the spher-  
 430 ical secondary. Thus, a  $2\sigma$  distribution footprint  $A_{2\sigma} > 1$  would represent a  
 431 footprint larger than the asteroid itself, thus indicating a highly unreliable  
 432 deployment. One would thus ideally aim for deployments such that  $A_{2\sigma} < 1$ .  
 433 Note that as long as there are uncertainties in a deployment (which is the  
 434 case here),  $A_{2\sigma}$  will always be greater than 0, and  $A_{2\sigma} \in [0, \infty)$ .

435 The expression in Eq. 8 allows defining a single figure of merit to measure  
 436 landing reliability, which, as is shown later by a Monte Carlo analysis valida-  
 437 tion, provides a simple and fast method to obtain a qualitative understanding  
 438 of the reliability of the landing opportunity.

439 In the next two subsections, we will analyze how the  $A_{2\sigma}$ -index value  
 440 appears in both asteroids for minimum and modified touchdown velocities.

#### 441 *4.2. Landing at minimum and modified touchdown speeds*

442 Figure 4 summarizes the results of the  $2\sigma$  distribution footprint,  $A_{2\sigma}$ ,  
 443 analysis for two binaries in the minimum touchdown speed case. The fact  
 444 that only small regions display values  $A_{2\sigma} \leq 1$  indicates that at the achieved

445 accuracies in navigation and deployment in Table 2, landing trajectories are  
 446 not robust enough to provide wider range of reliable landing locations.

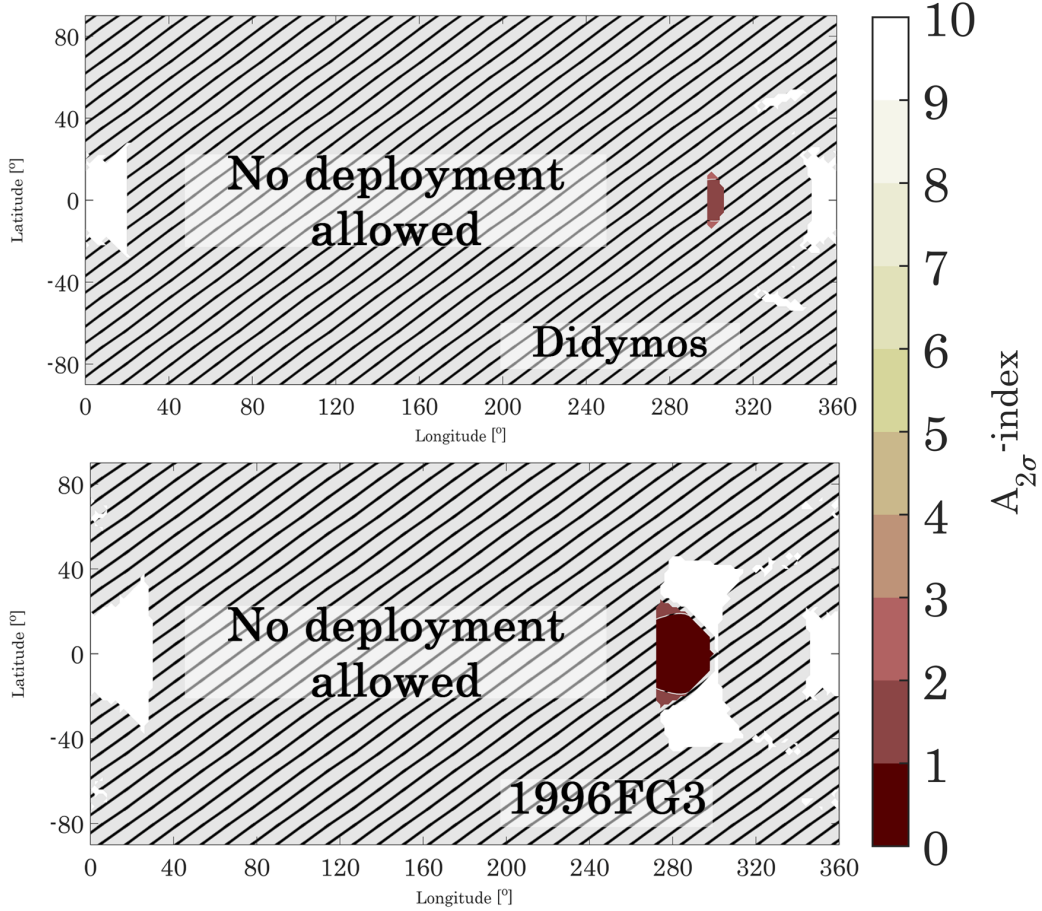


Figure 6:  $A_{2\sigma}$ -index for minimum touchdown speeds

447 With the introduced deployment model and the chosen arbitrary safe dis-  
 448 tance for deployment, Didymoon surface is almost unreachable at any point  
 449 except for very small, scattered islands in the far side. Even among those  
 450 reachable regions, only an area in near-equatorial latitudes, at  $300^\circ$ , there is

451 a very limited area that exhibit the  $A_{2\sigma}$ -index between 1 and 2. This region  
452 is rather more reliable, because trajectories are more energetic with higher  
453 touchdown speeds, therefore allow less propagation time for uncertainties.  
454 The results for Didymoon suggest that, deployment aiming minimum touch-  
455 down speeds may entail challenges, at least for given deployment model,  
456 distance and navigation uncertainties, that may be hard to overcome.

457 The deployments aiming minimum touchdown speeds to 1996 FG3-B sur-  
458 face appears to be more robust, although again in a reduced region. The  
459 most reliable region appears to be around the same region as observed in  
460 Didymoon. However, unlike the Didymoon case, this region extends about  
461  $20^\circ$  in both latitudinal and longitudinal directions. This robust region was  
462 previously identified for the hypothetical asteroid in Çelik and Sánchez [15],  
463 whose size is closer to 1996 FG3 (though slightly smaller) [15]. The existence  
464 of the same region in both binaries implies a first hand estimation about the  
465 reliable landing operations regardless of the target properties, even before  
466 generating a global map.

467 Investigating the minimum touchdown speeds allows us to understand  
468 the limits of this particular mission design problem. This information is un-  
469 doubtedly valuable during a mission design process. However, the minimum  
470 touchdown speeds do not always imply the optimal landing operations, as  
471 demonstrated in Fig. 6. It follows then that larger touchdown speeds than  
472 the minimum shall be attempted. A larger than the minimum touchdown  
473 speed implies a much faster descent trajectory, thus shorter landing opera-  
474 tions. With a straightforward reasoning, initial errors at the instant of de-  
475 ployment may have lesser time to propagate, hence have a smaller impact on

476 the dispersion. Nevertheless, the spring error is proportional to the velocity  
 477 magnitude, and thus the latter statement requires to be demonstrated.

478 As discussed in Section 3.1,  $\epsilon = 0.7$  is defined as the maximum allowed  
 479 value. Hence, a landing operation that precisely match this value is com-  
 480 puted. That means to scale landing speeds, so that the energy damping at  
 481 the instant of touchdown will ensure precisely the velocity magnitude that  
 482 closes the ZVS at L1 point and restrict the motion around the secondary  
 483 body. The maximum allowed touchdown speeds can therefore be as in Eq. 9  
 484 for each landing point:

$$v_{T/D}^{site} = \frac{v_{L1}^{site}}{\epsilon} \quad (9)$$

485 where  $v_{T/D}^{site}$  is touchdown speed and  $v_{L1}^{site}$  is the speed that closes the ZVS  
 486 at the L1 point at a given landing site.  $v_{T/D}^{site}$  is considered as the nominal  
 487 touchdown speed for this case, and since  $\epsilon$  value is conservatively defined,  
 488 no margin has been assumed. Figure 7 now shows the robustness of those  
 489 trajectories computed for the landing speeds as computed in Eq. 9, to the  
 490 same errors in deployments as described in Table 2.

491 Note that the color code is now different, and separated as the  $A_{2\sigma}$ -  
 492 index values changed. The figure demonstrates a dramatic increase in the  
 493 reliability of deployments to both targets. Total area of possible landing  
 494 sites have clearly expanded in both asteroids, about  $\sim 30\%$  of all 1996 FG3-B  
 495 surface and  $\sim 17\%$  of all Didymoon surface is now available for deployments  
 496 with the introduced deployment model.

497 Despite the increased possibilities for deployments on Didymoon surface,  
 498 no target site with  $A_{2\sigma} < 1$  is observed. The lowest value in this case is 1.29,

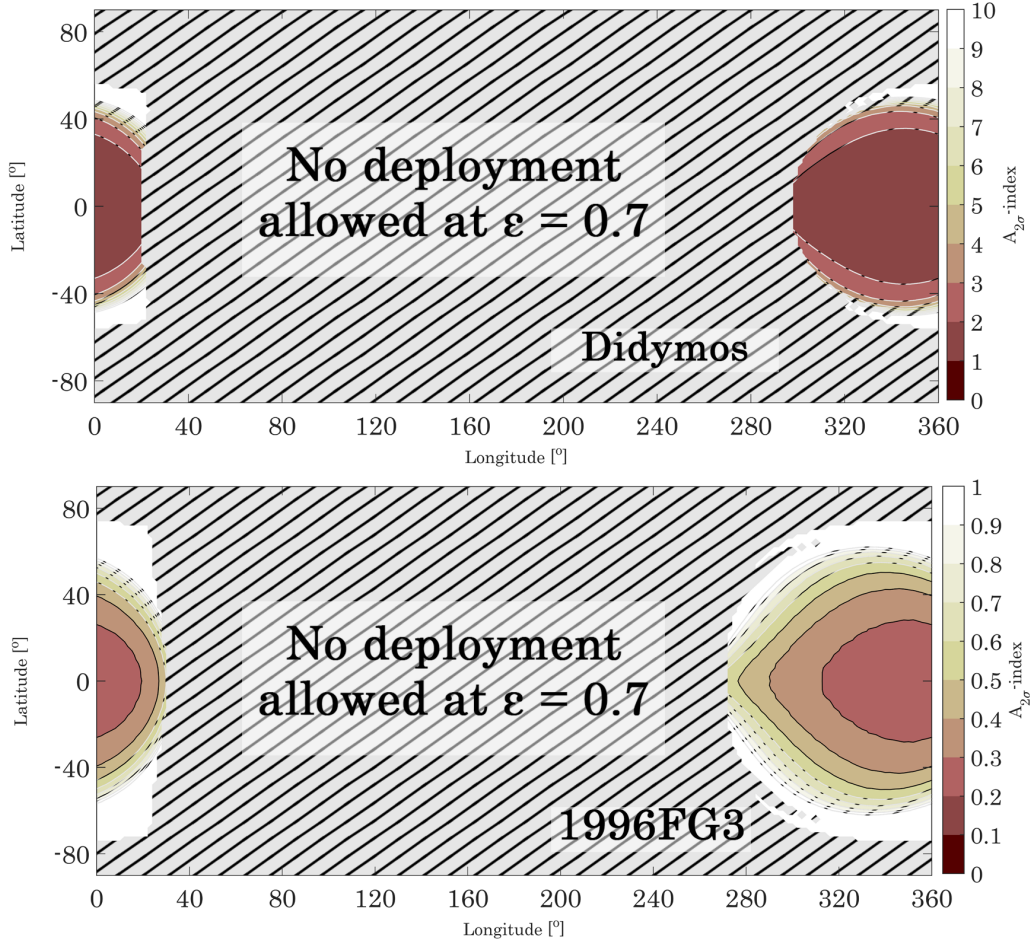


Figure 7:  $A_{2\sigma}$ -index for modified touchdown speeds

499 and it is observed in equator at  $334^\circ$  longitude. The  $A_{2\sigma}$ -index values remain  
 500 in between 1 to 2 times the cross sectional area of Didymoon for a wide region,  
 501 extending longitudes from  $300^\circ$  to  $20^\circ$  and latitudes up to  $35^\circ$ . This regions  
 502 would provide the highest reliability, though still with lower than what would  
 503 be expected from a reliable deployment ( $A_{2\sigma} \ll 1$ ). This result suggests that  
 504 the introduced deployment model, especially the deployment distance may

505 be responsible for this poor reliability in the Didymos case. Deployments  
 506 at lower altitude will likely to improve the reliability of landing. Finally, as  
 507 target latitude increases, reliability of deployments decreases. Mid-latitudes  
 508 display the lowest reliability with  $A_{2\sigma}$ -index  $\geq 10$ .

509 Deployments on the 1996 FG3-B surface, on the other hand, provides  
 510 much more reliable prospects with a much larger area of landing opportu-  
 511 nities. All possible regions have now shown  $A_{2\sigma} < 1$ , except small regions  
 512 in high-latitudes. The lowest  $A_{2\sigma}$  value is computed for  $1^\circ$  latitude and  $0^\circ$   
 513 longitude (i.e. approximately the tip of 1996FG3-B on the far side) as 0.24.  
 514  $A_{2\sigma}$ -index values smaller than 0.6 extend between  $280^\circ$  in the trailing edge to  
 515  $20^\circ$  in the leading edge, providing a numerous deployment opportunities that  
 516 are reliable. Unlike for the Didymoon case, there are still reliable opportu-  
 517 nities at mid-latitudes, up to approximately  $45^\circ$ - $50^\circ$ . This opens up possibly  
 518 interesting regions to be explored by a small lander, for the sizes of asteroid  
 519 moons as 1996 FG3-B.

520 The  $A_{2\sigma}$ -index offers quick assessment capability for a target landing site  
 521 with a very simple parameter. However, it is reasonable to verify how our  
 522 covariance based fast reliability analysis matches with Monte Carlo analyses,  
 523 which can account nonlinearities intrinsic to the dynamical model. Therefore,  
 524 Monte Carlo analysis was performed for each target landing locations in  
 525 order to verify the assertions made here about the reliability of deployments  
 526 with the  $A_{2\sigma}$ -index. The Monte Carlo analysis in this case constitutes 1000  
 527 randomly generated samples with the uncertainty values provided in Table  
 528 2. It is important note that, a Monte Carlo analysis with 1000 samples  
 529 represent statistics with  $\sim 5\%$  error  $3\sigma$  variance [37]. Furthermore, while the

530  $A_{2\sigma}$ -index computation took  $\sim 6$  hours in total for this case, the Monte Carlo  
 531 computations for this case took  $\sim 3$  days for the same case for one hemisphere  
 532 of one asteroid. The results are presented in Fig. 8.

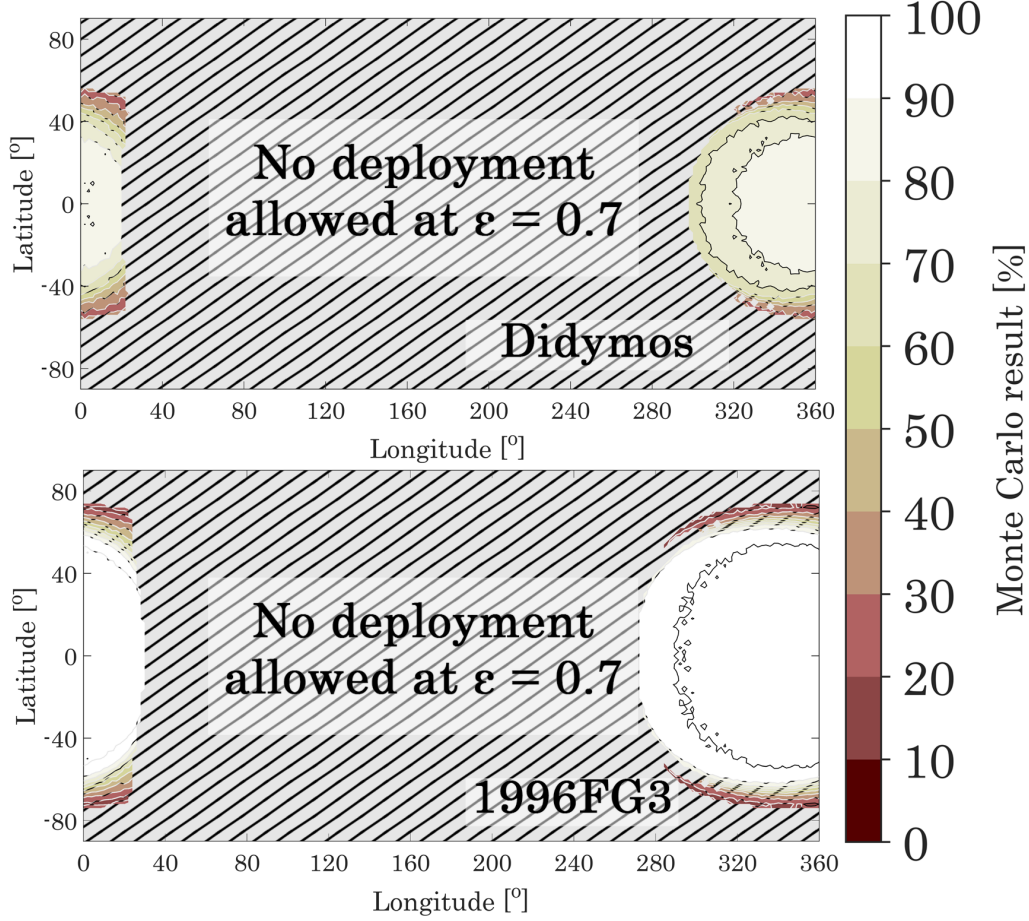


Figure 8: The Monte Carlo results.

533 In general, there is a very good agreement with our Monte Carlo analysis  
 534 and  $A_{2\sigma}$ -index results. Almost all regions in the 1996 FG3-B surface with  
 535  $A_{2\sigma}$ -index lower than 1 show Monte Carlo success rate greater than 95%. The  
 536 Monte Carlo analysis of the target site with the highest  $A_{2\sigma}$ -index certifies

537 that the probability of first touchdown is 100%. In fact, it appears that very  
 538 high  $A_{2\sigma}$  values can be evaluated as reliable for the 1996 FG3-B surface, since  
 539 the  $A_{2\sigma}$ -index of up to 0.8 in the 1996FG3 case exhibits Monte Carlo success  
 540 of greater than 90%. If we then assume a coefficient of restitution of 0.7 or  
 541 lower, one can be confident that the lander will remain in the surface of 1996  
 542 FG3-B, or binary systems whose properties similar to that.

543 The situation, on the other hand, is much more complex in Didymoon sur-  
 544 face. While the  $A_{2\sigma}$ -index is distributed homogeneous in a relatively larger  
 545 area in Fig. 7, Monte Carlo results for the same region reveal a fragile  
 546 condition. Indeed, our assertions for Didymoon was confirmed, and the de-  
 547 ployments to Didymoon surface is not at all reliable against the initial errors  
 548 with the assumption made. It appears that the  $A_{2\sigma}$ -index is less accurate for  
 549 a smaller binary according to the Monte Carlo results, but always in agree-  
 550 ment with it qualitatively. In this respect, the  $A_{2\sigma}$ -index works well. The  
 551 results, on the other hand, suggest that, when the uncertainties are the same,  
 552 the deployment distance must be closer to the Didymoon surface for more  
 553 reliable operations.

554 As a side note, although it is not explored in this work, it should also be  
 555 noted about the Monte Carlo analysis that allowing longer propagation time  
 556 ( $>12$  h) and higher number of samples in simulations may slightly alter the  
 557 presented success probabilities of the first touchdowns on both targets.

## 558 5. Conclusions

559 This paper investigated the reliability of ballistic landings on the secon-  
 560 daries of two previously proposed target binaries, Didymos and 1996 FG3.



561 Building a model on top of the previously developed algorithm [15], various  
 562 simulations were performed in order to assess statistical success of nominal  
 563 trajectories under the effect of deployment and navigation errors. It was  
 564 found that, landing trajectories to the regions with lowest possible touch-  
 565 down speeds are unavailable for short duration of deployment operations,  
 566 therefore prone to suffer from uncertainties. A simple scale-up procedure is  
 567 applied to touchdown speeds in order to increase their energy by means of  
 568 assuming a new, conservative coefficient of restitution, whose value is in har-  
 569 mony with observational findings and theoretical studies. Allowing higher  
 570 touchdown speeds have greatly increased the reachable area and reliability  
 571 of deployment operations for given deployment model.

572 A covariance analysis was performed with realistically defined uncertain-  
 573 ties in order to assess the robustness of the available trajectories. Reliable  
 574 regions are identified via a simple index defined by the projected area of  
 575 the uncertainty ellipsoid in the topocentric frame of the target landing sides,  
 576 and cross-sectional area of the target asteroid. This simple index is a useful  
 577 measure, despite its simplicity, and allows a quick qualitative investigation  
 578 of robust landing operations. The usefulness of the index is in fact certified  
 579 by the Monte Carlo analysis. Thus, the robust design optimization of such  
 580 mission can easily include this covariance based reliability index, which can  
 581 provide sufficiently accurate reliability results to be used in the process.

582 The deployment reliability within the available regions are much higher in  
 583 the far side of the binary moons, with very small deployment speeds. Near-  
 584 equatorial regions are by far the most robust, with more longitudes in the  
 585 trailing side. Larger binary moons, at least sizes on the order of 1996FG3

586 or more, also provide opportunities to explore higher latitude regions, which  
587 might be of interest to understand the binary formation. The deployment  
588 operations for mid- and high-latitudes, however, seem to be much less reliable  
589 in small binaries with the proposed deployment strategy. Particularly, there  
590 are no deployment opportunities identified for polar latitudes in both sample  
591 asteroids. However, the reliability analysis in this paper suggests that, in  
592 order to achieve higher impact probabilities in smaller asteroid cases, a more  
593 accurate deployment mechanism and navigation system in motherships, and  
594 closer deployments are paramount. However, it should be noted that for the  
595 latter, that dynamical stability of mothership motion and operational risk  
596 due to the proximity to the surface must carefully be assessed.

597 The analyses in this paper revealed regions of reliable ballistic landing  
598 through the covariance-based reliability index. This index would provide a  
599 simple, straightforward and efficient analysis framework. The results of that  
600 can also be used in the robust optimization of the deployment and descent  
601 operations where the reliability of the landing trajectory is also maximized in  
602 the design process. The final results on the target binary asteroids would also  
603 provide useful inputs to the current and the future small body exploration  
604 missions that carry small landers to be deployed to the surface via ballistic  
605 trajectories.

## 606 **Acknowledgement**

607 Onur Celik acknowledges MEXT research scholarship from Japanese gov-  
608 ernment and short-term research grant from ROB. The authors would like  
609 to thank Massimo Casasco for his valuable inputs about the navigation and

610 deployment errors.

## 611 References

- 612 [1] J. L. Margot, M. C. Nolan, L. A. M. Benner, S. J. Ostro, R. F.  
613 Jurgens, J. D. Giorgini, D. B. Campbell, Binary asteroids in the  
614 near-Earth object population, *Science* 296 (5572) (2002) 1445–1448.  
615 doi:10.1126/science.1072094.
- 616 [2] A. W. Harris, M. A. Barucci, J. L. Cano, A. Fitzsimmons,  
617 M. Fulchignoni, S. F. Green, D. Hestroffer, V. Lappas, W. Lork,  
618 P. Michel, D. Morrison, D. Payson, F. Schäfer, The European Union  
619 funded NEOShield project: A global approach to near-Earth object  
620 impact threat mitigation, *Acta Astronautica* 90 (1) (2013) 80–84.  
621 doi:10.1016/j.actaastro.2012.08.026.
- 622 [3] J. P. Sanchez, C. Colombo, Impact hazard protection efficiency by a  
623 small kinetic impactor, *Journal of Spacecraft and Rockets* 50 (2) (2013)  
624 380–393. doi:10.2514/1.A32304.
- 625 [4] M. A. Barucci, A. F. Cheng, P. Michel, L. A. M. Benner, R. P.  
626 Binzel, P. A. Bland, M. Zolensky, MarcoPolo-R near earth asteroid sam-  
627 ple return mission, *Experimental Astronomy* 33 (23) (2012) 645–684.  
628 doi:10.1007/s10686-011-9231-8.
- 629 [5] R. C. Anderson, D. Scheeres, S. Chesley, the BASiX Science Team, A  
630 Mission Concept to Explore a Binary Near Earth Asteroid System, in:  
631 Proceedings of the 45<sup>th</sup> Lunar and Planetary Science Conference, The  
632 Woodlands, Texas, 2014, March 17–21, Paper number 1777.

- 633 [6] A. F. Cheng, J. Atchison, B. Kantsiper, A. S. Rivkin, A. Stickle,  
634 C. Reed, S. Ulamec, Asteroid Impact and Deflection Assessment  
635 mission, *Acta Astronautica* 115 (OctoberNovember) (2015) 262–269.  
636 doi:10.1016/j.actaastro.2015.05.021.
- 637 [7] A. G. I. Carnelli, R. Walker, Science by Cubes: Opportunities to In-  
638 crease AIM Science Return, in: *Proceedings of the 4<sup>th</sup> Interplanetary*  
639 *CubeSat Workshop*, London, UK, 2015, May 27–28, Paper number  
640 2015.B.3.1.
- 641 [8] O. Karatekin, D. Mimoun, N. Murdoch, B. Ritter and N. Gerbal, The  
642 Asteroid Geophysical EXplorer (AGEX) to Explore Didymos, in: *Pro-*  
643 *ceedings of the 5<sup>th</sup> Interplanetary CubeSat Workshop*, Oxford, UK, 2016,  
644 May 28–29, Paper number 2016.A.2.1.
- 645 [9] S. Ulamec, L. O’Rourke, J. Biele, B. Grieger, R. Andres, S. Lodiot,  
646 P. Munoz, A. Charpentier, S. Mottola, J. Knollenberg, M. Knapmeyer,  
647 E. Kuhrt, F. Scholten, K. Geurts, M. Maibaum, C. Fantinati, O. Kuche-  
648 mann, V. Lommatsch, C. Delmas, E. Jurado, R. Garmier, T. Mar-  
649 tin, Rosetta Lander - Philae: Operations on comet 67P/Churyumov-  
650 Gerasimenko, analysis of wake-up activities and final state, *Acta Astro-*  
651 *nautica* 137 (August) (2017) 38–43. doi:10.1016/j.actaastro.2017.04.005.
- 652 [10] S. Tardivel, D. J. Scheeres, Ballistic Deployment of Science Packages on  
653 Binary Asteroids, *Journal of Guidance, Control, and Dynamics* 36 (3)  
654 (2013) 700–709. doi:10.2514/1.59106.
- 655 [11] S. Tardivel, P. Michel, D. J. Scheeres, Deployment of a lander on the

- 656 binary asteroid (175706) 1996 FG<sub>3</sub>, potential target of the european  
657 MarcoPolo-R sample return mission, *Acta Astronautica* 89 (August–  
658 September) (2013) 60–70. doi:10.1016/j.actaastro.2013.03.007.
- 659 [12] S. Tardivel, C. Lange, S. Ulamec, J. Biele, The Deployment of  
660 MASCOT-2 to Didymoon, in: *Proceedings of the 26<sup>th</sup> AAS/AIAA Space*  
661 *Flight Mechanics Meeting*, Napa, California, 2016, February 14–18, Pa-  
662 per number: AAS 16-219.
- 663 [13] S. Tardivel, Optimization of the Ballistic Deployment to the Secondary  
664 of a Binary Asteroid, *Journal of Guidance, Control, and Dynamics*  
665 39 (12) (2016) 2790–2798. doi:10.2514/1.G000593.
- 666 [14] F. Ferrari, M. Lavagna, Consolidated phase a design of Asteroid Impact  
667 Mission: MASCOT-2 landing on binary asteroid didymos, *Advances in*  
668 *the Astronautical Sciences* 158 (October) (2016) 3759–3769.
- 669 [15] O. Çelik, J. P. Sanchez, Opportunities for Ballistic Soft Landing in Bi-  
670 nary Asteroids, *Journal of Guidance, Control, and Dynamics* 40 (6).  
671 doi:10.2514/1.G002181.
- 672 [16] J. P. Sánchez, D. García Yarnoz, C. McInnes, Near-Earth asteroid  
673 resource accessibility and future capture mission opportunities, in:  
674 *Global Space Exploration Conference*, International Astronautical Fed-  
675 eration, Washington, USA, 2012, May 22–24. Paper number: GLEX-  
676 2012.11.1.5x12412.
- 677 [17] V. Szebehely, *Theory of Orbits*, Academic Press: New York, 1967.

- [18] S. Tardivel, D. J. Scheeres, P. Michel, S. van Wal, P. Sanchez, Contact Motion on Surface of Asteroid, *Journal of Spacecraft and Rockets* 51 (6) (2014) 1857–1871. doi:10.2514/1.A32939.
- [19] S. Ulamec, C. Fantianti, M. Maibaum, K. Geurts, J. Biele, S. Jansen, L. O’Rourke, Rosetta Lander–Landing and Operations on Comet 67P/Churyumov–Gerasimenko, *Acta Astronautica* 125 (August–September) (2016) 80–91. doi:10.1016/j.actaastro.2015.11.029.
- [20] H. Yano, T. Kubota, H. Miyamoto, T. Okada, D. Scheeres, Y. Tagagi, K. Yoshida, M. Abe, S. Abe, O. Barnouin-Jha, Touchdown of the Hayabusa Spacecraft at the Muses Sea on Itokawa, *Science* 312 (5778) (2006) 1350–1353. doi:10.1126/science.1126164.
- [21] J. Biele, S. Ulamec, M. Maibaum, R. Roll, L. Witte, E. Jurado, P. Munoz, W. Arnold, H.-U. Auster, C. C. et al., The Landing(s) of Philae and Inferences About Comet Surface Mechanical Properties, *Science* 349 (6247) (2015) 1–6. doi:10.1126/science.aaa9816.
- [22] J. Biele, L. Kessler, C. D. Grimm, S. Schröder, O. Mierheim, M. Lange, T.-M. Ho, Experimental Determination of the Structural Coefficient of Restitution of a Bouncing Asteroid LanderarXiv:1705.00701.  
URL <http://arxiv.org/abs/1705.00701>
- [23] T. Ho, J. Biele, C. Lange, AIM MASCOT-2 Asteroid Lander Concept Design Assessment Study, Tech. rep., German Aerospace Center (DLR) (2016).

- 700 [24] S. Sawai, J. Kawaguchi, D. J. Scheeres, N. Yoshikawa, M. Ogasawara,  
701 Development of a Target Marker for Landing on Asteroids, *Journal of*  
702 *Spacecraft and Rockets* 51 (4) (2014) 1857–1871. doi:10.2514/2.3723.
- 703 [25] T. Kubota, S. Sawai, T. Hashimoto, J. Kawaguchi, Collision dynamics  
704 of a visual target marker for small-body exploration, *Advanced Robotics*  
705 51 (14) (2014) 1857–1871. doi:10.1163/156855307782227426.
- 706 [26] O. Çelik, J. P. Sanchez, O. Karatekin, B. Ritter, Analysis of nat-  
707 ural landing trajectories for passive landers in binary asteroids : A  
708 case study for (65803) 1996GT Didymos, in: 5<sup>th</sup> Planetary Defence  
709 Conference, 2017, May 15–19. Paper number: IAA-PDC17-03-P03.  
710 doi:10.13140/RG.2.2.34443.90405.
- 711 [27] L. Dell’Elce, N. Baresi, S. Naidu, L. Benner, D. Scheeres,  
712 Numerical investigation of the dynamical environment of 65803  
713 Didymos, *Advances in Space Research* 59 (5) (2016) 1304–1320.  
714 doi:10.1016/j.asr.2016.12.018.
- 715 [28] F. Damme, H. Hussmann, J. Oberst, Spacecraft orbit lifetime within  
716 two binary near-Earth asteroid systems, *Planetary and Space Science*-  
717 doi:10.1016/j.pss.2017.07.018.
- 718 [29] R. Walker, D. Binns, I. Carnelli, M. Kueppers, A. Galvez, CubeSat Op-  
719 portunity Payload Intersatellite Network Sensors (COPINS) on the ESA  
720 Asteroid Impact Mission (AIM), in: Proceedings of the 5<sup>th</sup> Interplane-  
721 tary CubeSat Workshop, Oxford, UK, 2016, may 24–25. Paper number  
722 2016.B.1.2.

- 723 [30] G. Gomez, A. Jorba, J. J. Masdemot, C. Simo, Study of the Transfer  
724 from the Earth to a Halo Orbit Around the Equilibrium Point L1 56 (4)  
725 (1992) 541–562.
- 726 [31] O. Çelik, O. Karatekin, B. Ritter, J. P. Sanchez, Reliability Analysis  
727 of Ballistic Landing in Binary Asteroid 65803 (1996GT) Didymos un-  
728 der Uncertainty and GNC Error Considerations, in: 26th International  
729 Symposium on Spaceflight Dynamics, Vol. ists14, Matsuyama, Japan,  
730 2017, Paper number: a90510.
- 731 [32] F. Ferrari, M. Lavagna, Ballistic landing design on binary aster-  
732 oids: The AIM case study, *Advances in Space Research* (2017) 1–  
733 16doi:10.1016/j.asr.2017.11.033.
- 734 [33] E. Canalias, A. Blazquez, E. Jurado, T. Martin, Philae Descent Tra-  
735 jectory Computation and Landing Site Selection on Comet Churyumov-  
736 Gerasimenko, in: *Proceedings of 23<sup>rd</sup> International Symposium on*  
737 *Spaceflight Dynamics*, Pasadena, California, 2012, Oct 29–Nov 2. Pa-  
738 per number GC-2.
- 739 [34] J.-P. Sanchez, O. Çelik, Landing in Binary Asteroids : A Global Map  
740 of Feasible Descent Opportunities for Unpowered Spacecraft, in: *In-*  
741 *ternational Astronautical Congress (IAC)*, Adelaide, Australia, 2017,  
742 September 25–29. Paper number: IAC-17,C1,8,7,x37745.
- 743 [35] M. Casasco, J. Gil-Fernandez, G. Ortega, I. Carnelli, Guidance Naviga-  
744 tion and Control Challenges for the ESA Asteroid Impact Mission, in:



- 745 30th International Symposium on Space Science and Technology (ISTS  
746 2017), Matsuyama, Japan, 2017, pp. 1–6.
- 747 [36] W. E. Wiesel, Modern orbit determination, Aphelion Press, 2003.
- 748 [37] M. Ceriotti, J. P. Sanchez, Control of asteroid retrieval trajec-  
749 ries to libration point orbits, *Acta Astronautica* 126 (2016) 342–353.  
750 doi:10.1016/j.actaastro.2016.03.037.

2018-03-14

# A comparative reliability analysis of ballistic deployments on binary asteroids

Çelik, Onur

Elsevier

---

Çelik O, Sánchez JP, Karatekin Ö, Ritter B, A comparative reliability analysis of ballistic deployments on binary asteroids, Acta Astronautica, Volume 156, Issue March 2018, pp. 308-316  
<http://dx.doi.org/10.1016/j.actaastro.2018.03.020>

*Downloaded from Cranfield Library Services E-Repository*